N91-22152

LASER DRIVEN LAUNCH VEHICLES FOR CONTINUOUS ACCESS TO SPACE

C.J. Rollins, A. Bailey, A. Gelb, M. Gauthier, C. Goldey
E. Lo, D. Resendes, D. Rosen, and G. Weyl
Physical Sciences Inc.
Andover, MA 01810

ABSTRACT

The availability of megawatt laser systems in the next century will make laser launch systems from ground to orbit feasible and useful. Systems studies indicate launch capabilities of 1 ton payload per gigawatt laser power. This corresponds to 20 Kg payloads with 20 megawatt lasers. A launch repetition frequency of one payload every 10 min would allow delivery of parts for assembly of large space structures, and would allow resupply of space stations on a continuous basis. Recent research in ground-to-orbit laser propulsion has emphasized laser supported detonation wave thrusters driven by repetitively pulsed infrared lasers. In this propulsion concept each laser repetition cycle consists of two pulses. A lower energy first pulse is used to vaporize a small amount of solid propellant and then after a brief expansion period of a few microseconds, a second and higher energy laser pulse is used to drive a detonation wave through the expanded vapor. Temperatures of order 10,000 K are achieved. During a several millisecond intercycle delay, expansion of the hot vapor converts thermal energy to directed kinetic energy. High specific impulses of ~600 to 800s are achievable at energy conversion efficiencies of ~20 to 40 percent. The physics of such thrusters has been explored both theoretically and in the laboratory. We report here the results of numerical studies comparing the detonation wave properties of various candidate propellants, and the simulation of thruster performance under realistic conditions. Experimental measurements designed to test the theoretical predictions are also presented. We discuss measurements of radiance and opacity in absorption waves, and mass loss and momentum transfer. These data are interpreted in terms of specific impulse and energy conversion efficiency. Directions for future research are indicated.

The availability of megawatt laser systems in the next century will make laser launch systems from ground to orbit feasible and useful. Systems studies indicate launch capabilities of 1 ton payload per gigawatt laser power. This corresponds to 20 Kg payloads with 20 MW lasers. A launch repetition frequency of one payload every 10 min would allow delivery of parts for assembly of large space structures, and would allow resupply of space stations on a continuous basis (Figure 1).

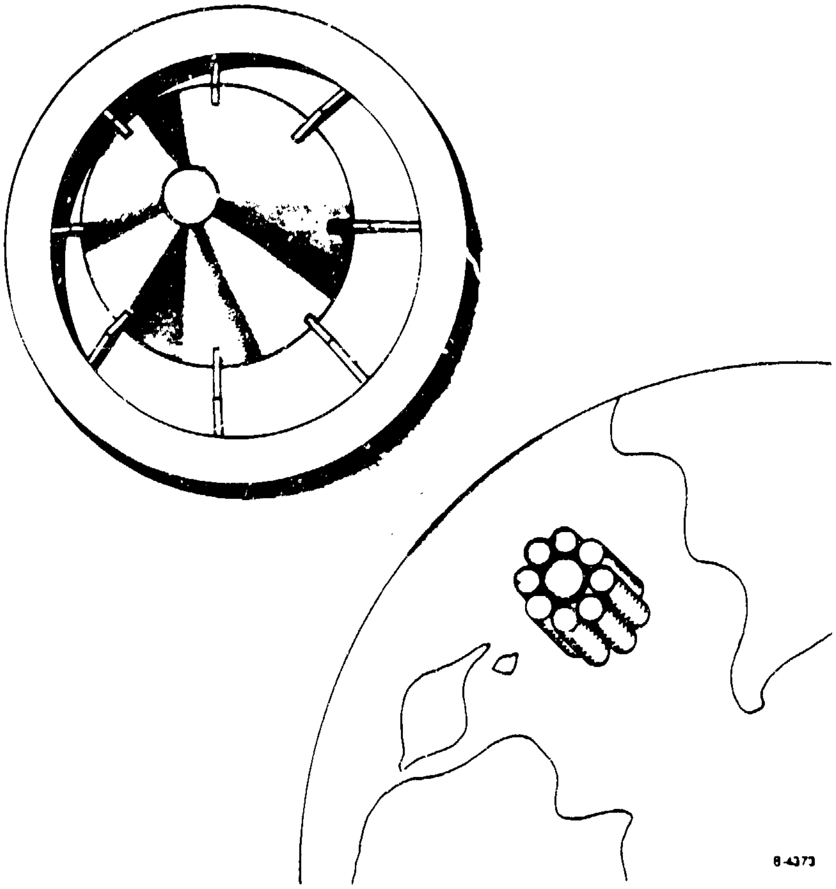

Figure 1. Laser propelled ground-to-orbit launch vehicle

Recent work has been conducted under the SDIO Laser Propulsion Program to demonstrate feasibility of the concept through fundamental research, with an eye toward future applications. In another symposium paper, Jordin Kare (ref. 1) reviews the status of pulsed laser propulsion and identifies future applications. In this paper, we focus on the current basic research which forms the foundation for future advances. We emphasize here a research effort oriented toward the earth to low-earth orbit problem which offers the most immediate challenge, and promises the most immediate rewards, but it should be kept in mind that simple and straightforward extensions of this effort can easily be brought to frustion in support of inter-orbit and inter-planetary mission opportunities.

Recent research in ground-to-orbit laser propulsion has emphasized laser supported detonation wave thrusters driven by repetitively pulsed infrared laser. The detonation wave thruster concept was introduced by Pirri and Weiss (ref. 2). The current work has centered on a double pulse version invented by Reilly (ref. 3), and reintroduced by Kantrowitz (ref. 4) in simplified form for use in ground-to-orbit launches of small payloads. In this propulsion concept each laser repetition cycle consists of two pulses. A lower energy first pulse is used to vaporize a small amount of solid propellant and then after a brief expansion period of a few microseconds, a second and higher energy laser pulse is used to drive a detonation wave through the expanded vapor. Temperatures of order 10,000 K are achieved. During a several millisecond intercycle delay, expansion of the hot vapor converts thermal energy to directed kinetic energy. High specific impulses of ~ 600 to 800s are achievable at energy conversion efficiencies of ~ [illegible] to 40 percent. Figure 2 illustrates the thruster concept during each of the two laser pulses of a thrust cycle.

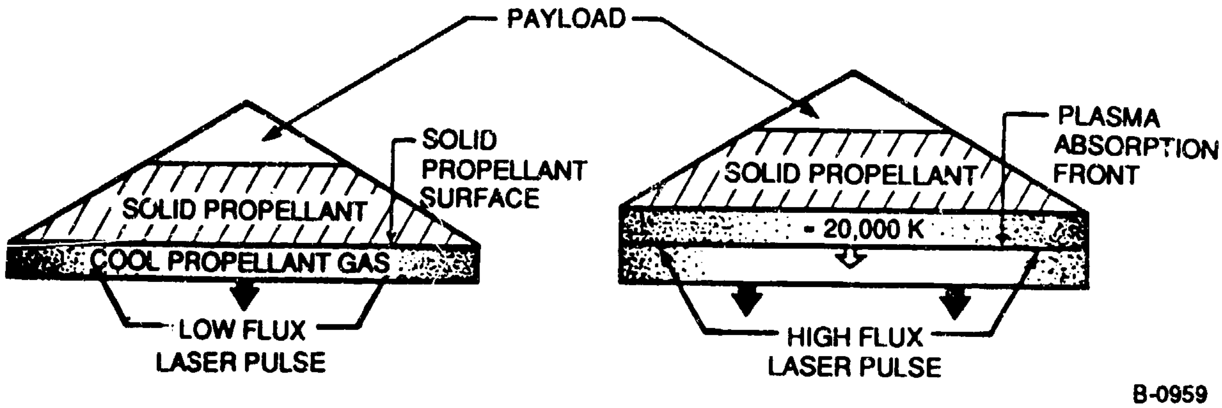

Figure 2. Laser-sustained-detonation wave rocket

The physics of such thrusters has been explored both theoretically and in the laboratory. We report here the results of numerical studies comparing the detonation wave properties of various candidate propellants, and the simulation of thruster performance under realistic conditions. Experimental measurements designed to test the theoretical predictions are also presented.

Detonation wave properties

In a detonation wave thruster, several requirements must be made on the propellant properties to insure proper operation. Among the important considerations are: moderate heat of vaporization, short optical absorption depth to the laser beam, low ionization threshold in the gas phase, and low average atomic weight. These requirements combine to ensure that there is a proper amount of mass delivered during laser irradiation, minimal mass flow between pulse pairs, and uniform processing of the gas during the high irradiance detonation wave portion of the thruster cycle. To achieve this last condition, it is necessary that a detonation wave can be formed quickly in the high irradiance portion of the thruster cycle, and that the wave must be thin compared to the gas slug which has been produced by the low irradiance portion of the cycle. Failure on the first point would result in considerable mass being ejected from the thruster at low specific impulse, while failure on the second point causes non-uniform processing of the gas, with consequent low energy conversion efficiency.

In order to address the differences between candidate propellants with respect to detonation wave properties, we have constructed a computer code which simulates such waves under assumed conditions of steady state and local thermodynamic equilibrium. The details of the code have been published elsewhere (ref. 5). For the present paper, we have chosen two specific cases to illustrate the utility of the method. Figures 3a and 3b show the density versus distance profiles of two

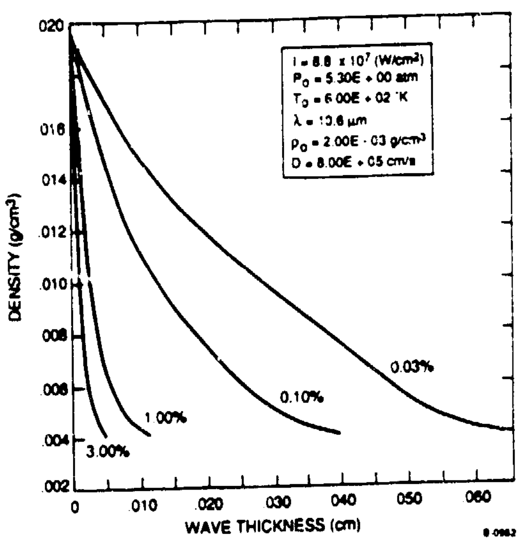

Figure 3a. Absorption wave for water propellant seeded with Li at indicated percentages, density versus position

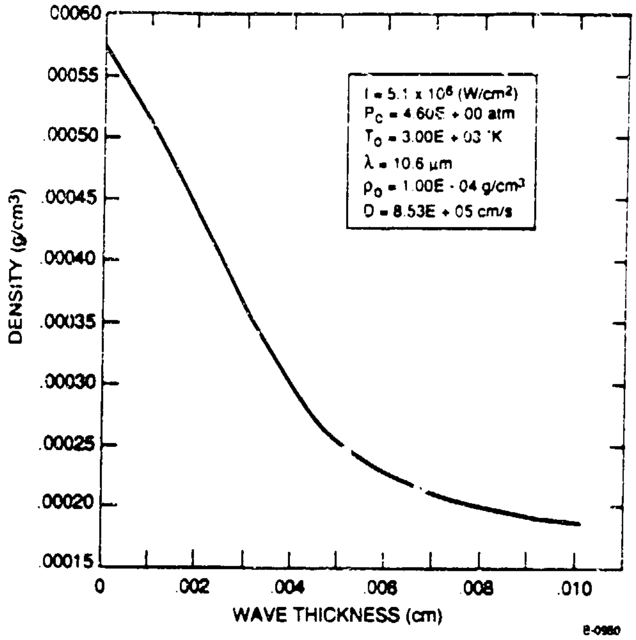

Figure 3b. Absorption wave for lithium hydride, density versus position

candidate propellants, water and lithium hydride, under conditions of comparable detonation wave velocity, which in turn implies comparable specific impulse. In these figures, the laser is incident from the left. Two factors are of particular importance in the comparison. The first is that at comparable specific impulse, considerably higher irradiance is required to operate using water (ice) as the propellant. This is because of the corresponding higher heats of vaporization, dissociation, and ionization of ice, as compared to lithium hydride. The second important feature is that in order to achieve the required thin detonation wave structure ($\lesssim$ 100 μm is desirable for a ~ 1 cm gas slug), it is necessary to add substantial atom fractions of a low ionization potential material to the water. On-going research in this area includes incorporation of non-equilibrium properties, exploration of other possible propellants, and assessment of the unsteady portions of the process.

Reactive flow modeling

Once the detonation wave processing is complete, the hot gas expands away from the rocket. Both electron-ion and atom-atom recombination take place in this expansion phase of the thrust cycle. In order to adequately describe the non-equilibrium aspects of these recombination processes, we have constructed a hydrocode which includes finite rate kinetics for the important reactions. The details of this code have been presented elsewhere (ref. 6). For the present context, we have chosen to emphasize a dependence on parameter variations for a particular propellant.

A variety of different cases was simulated. To most clearly identify the effects of different parameters, a base case was chosen for which the effect of perturbations were examined. This base case was stoichiometrically COH_2, that is one mole of carbon to one mole of oxygen to two moles of hydrogen. A mixture of this molar concentration is produced by the breakdown of a polyacelal resin. A 2 cm thick gas slug with a density of 2×10^{-3} grams/cm^3 and a temperature of 15,000 K was used, where the slug was initially at rest with respect to the base of the rocket and allowed to expand one dimensionally into vacuum. This case produced an impulse of 730s with a coupling of 36 dyne-s/Joule and an energy efficiency of 33 percent (neglecting radiation losses).

The results (see Table 1) clearly demonstrate the advantages of a dense gas slug over a more diffuse one. At low densities the recombination rate drops precipitously, substantially reducing the impulse. If a lower mass removal rate per pulse is needed, it is preferable to reduce the slug thickness rather than lower its density. If this drives one to an excessively thin slab which deposits its

Table 1. Gas expansion simulation results

Fuel	Temper-ature	Mesh Points	Gas Slug (cm)	CO Recombina-tion (%)	Density (g/cm^3)	Impulse (s)	Impulse/ Energy (dyne-s/ J)	Effi-ciency (%)
COH_2	15,000	40	2	47	2×10^{-3}	730	36	33
COH_2	15,000	80	2	54	2×10^{-3}	760	38	36
COH_2	15,000	40	0.2	33	2×10^{-3}	650	34	29
COH_2	10,000	40	2	33*→74	2×10^{-3}	620	42	32
COH_2	15,000	40	2	0 (forced)	2×10^{-3}	550	27	18
COH_4	15,000	40	2	[illegible]	2×10^{-3}	840	33	34
COH_2	15,000	40	2	16	2×10^{-4}	640	32	25
COH_2	15,000	40x30	2 x 50	44	2×10^{-3}	610	31	24

impulse over two brief an interval, then propellants for which recombination is unimportant should be considered. Going to lower temperatures improves the impulse per unit energy, but, as expected, the total impulse suffers.

On-going research seeks to model a wide variety of propellants and to incorporate the effects of specific projectile geometries.

Experimental work

In conjunction with the theory and modeling activities, an experimental effort has been conducted to verify the validity of the conclusions. In particular, measurements have been made of the effective heat of mass removal, and the delivered impulse for various propellant materials, along with various optical and radiometric measurements. To illustrate some of the ongoing work, we offer an example from experiments designed to visualize the detonation wave as it processes a slab of vaporized propellant.

In order to visualize these phenomena in our experiments, we have used a technique to form temporally and spatially resolved images of the plasma radiance, and opacity to its own radiance. The technique is a two-dimensional, temporally resolved generalization of a method developed by Goncharov (ref. 7). The key to the technique involves positioning on the side of the plasma opposite the observation site an imaging lens and a concave reflecting mirror whose surface has been divided into a fine pattern of alternating reflective and non-reflective (opaque) strips. With appropriately chosen and positioned imaging lenses, the radiance distribution recorded by the observation camera consists of a striped pattern with the amplitude of adjacent stripes being proportional to, respectively, the local plasma radiance and the plasma radiance amplified by its self-transmission through the plasma. By comparing the relative intensities of adjacent stripes and knowing the effective transmission of the retro-reflecting optical components, one then finds the spatial profile of plasma transmission.

Detonation waves were observed in soda lime glass vapor (Figure 4). The figure consists, in principal, of eight exposures proceeding raster fashion from the lower left to the upper right. The first two frames precede the introduction of the high intensity laser pulse and are consequently black.

A lower intensity laser pulse was used about 6 μs before the main pulse to vaporize some of the glass target. The vapor from this pulse occupies a zone extending about a centimeter from the target surface at the time when the high intensity pulse is introduced. This second pulse

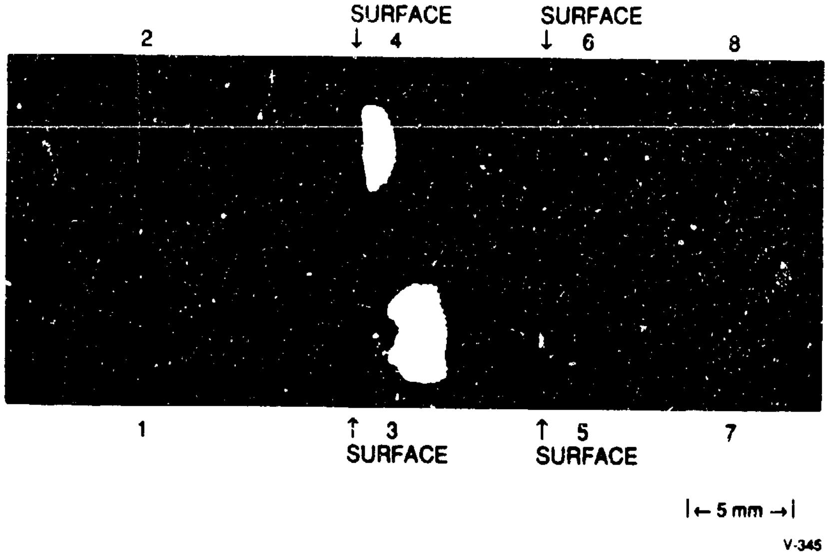

Figure 4. Self-transmission framing photo for double pulse experiments on glass

ignites a laser supported detonation wave wave and carries it at speeds approaching 10^6 cm/s. The wave is clearly visible in the third frame at a position several millimeters off the target surface. In the intervening microsecond between the third and fourth frames, the wave would be expected to propagate to the edge of the initial pulse vapor distribution, where the rarefied gas density would no longer support an opaque wave. The fourth frame confirms this expectation, showing that laser light is once again being admitted to the surface. By the fifth frame, the TEA laser pulse has considerably weakened and is able to support only a comparatively tenuous plasma near the target surface. No exposure at all is detectable in the subsequent frames.

Future Research

While the current paper has focused on some particular examples to demonstrate the character of current research, simple extension of the research will lend themselves to a wide variety of future laser propulsion applications. In particular, there may be advantages in exploring lower specific impulse propellants for a multistage ground-to-orbit concept, or to make use of radio frequency free-electron laser waveforms. High specific impulse systems and nozzled thrusters may lend themselves more to in space missions. In any event, transition from the current research phase to 21st century actual systems appears straightforward.

REFERENCES

1. "Ground-to-Orbit Laser Propulsion - Advanced Applications," J.T. Kare, these proceedings.

2. Pirri, A.N. and Weiss, R.F., "Laser Propulsion," AIAA Reprint 72-719, Fifth Fluid and Plasma Dynamics Conference (1972).

3. Douglas-Hamilton, D.H., Kantrowitz, A., and Reilly, D.A., "Laser Assisted Propulsion Research," Progress in Astronautics and Aeronautics, Vol. 61, K.W. Billmann, ed., AIAA, New York, 271 (1978).

4. Kantrowitz, A., "Laser Propulsion to Earth Orbit," Workshop on Laser Propulsion, Vol. 2, J.T.Kare, Ed. (LLNL, Livermore, CA, 1987).

5. Rollins, C.J., Bailey, A., Gelb, A., Resendes, D., and Weyl, G., "Evaluation of Laser Supported Detonation Wave Thrusters for Ground-to-Orbit Launch," AIAA 89-1914, AIAA 20th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Buffalo, NY, June 1989.

6. Rollins, C., Bailey, A., Gelb, A., Rosen, D., Weyl, G. and Wu, P., "Issues in Laser Propulsion," PSI SR-334, and Proceedings 1987 SDIO Workshop on Laser Propulsion (to be published), Lawrence Livermore, 1987.

7. Goncharov, et al., Sov. J. Quant. Electron., Vol. 3, No. 1 (1973).